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ROBUST SYSTEMS FOR INTERRELATED CONTROL OF TURBOGENERATORS UNDER UNCERTAINTY CONDITIONS

A method for synthesizing a controller for the single-machine power system with a turbogenerator is proposed, which ensures the controller robustness relative to the operating mode parameters. The synthesized controller performs the functions of a system stabilizer as to the reduction of low-frequency oscillations and at the same time coordinates operation of the automatic turbogenerator excitation regulators and automatic turbine rotation speed regulators.

Key words: *turbogenerator, robust control, system stabilizer.*

Introduction

During operation of turbogenerators low-frequency oscillations of the turbogenerator shafting occur in the power system. They are caused by load changes, commutations in the system, non-synchronous switching, short circuits, etc. To ensure static and dynamic stability of turbogenerators, automatic excitation regulators (AER) of the turbogenerators and automatic rotation speed regulators (ARSR) of the turbine are used [2]. The task of reducing the turbogenerator low-frequency electromechanic oscillations is implemented by AER channel according to voltage network or according to the generator rotor rotation speed. In foreign AER the rotor rotation speed stabilization channel is a separate logic unit referred to as power system stabilizer (PSS). Commonly, PSS is formed as a correction lead-lag compensator [6].

There exists a common practice of synthesizing AER and ARSR independently. However, these regulators have identical control channels such as turbogenerator shafting rotation speed and, therefore, independent synthesis could have a negative influence on their joint operation [1, 4]. Thus, there arises a problem of synthesizing an interrelated control system of the turbogenerator which simultaneously adjusts operation of AER and ARSR and the main aim of which is implementation of the system stabilizer function.

Synthesis of the excitation and rotation speed control system is based on the linearized model for the selected points. The controller, synthesized in this way, may not provide a sufficient control accuracy and stability for all modes. In addition, there are other sources of the model uncertainty: inaccurate electromagnetic and mechanical parameters of the turbogenerators and turbines, nonlinear dependence of the parameters on the modes due to saturation or changes of the active resistance with temperature change, etc. Therefore, there is a problem of checking the existing controllers for robustness and synthesis of the controllers with improved properties as to their robustness. In the modern control theory robustness is understood as the controller property to maintain stability and control quality under uncertainty of the control object parameters in certain limits.

The work aim is to develop a method for synthesis of the turbogenerator system stabilizer that will be robust in relation to the parameters of interrelated operating mode in the sense of providing coordinated operation of AER and ARER in the power system.

Research results

For the research a simplified mathematical model of the generator was used. The generator is connected to the infinite-power electric system through an external resistance which simulates a transformer and an electricity transmission line. The model takes into account AER that includes only voltage control channel. The circuit, presented in Fig. 1, includes a simplified model linearization in the fixed operating mode. Constants К1 – К6, obtained during linearization of the model of the generator with AER, depend both on the turbo generator and electric system parameters as well as on the operating mode parameters. Explicit expressions for these constants are given in [6]. A lower part of Fig. 1 includes also a model of the turbines with ARSR [2].

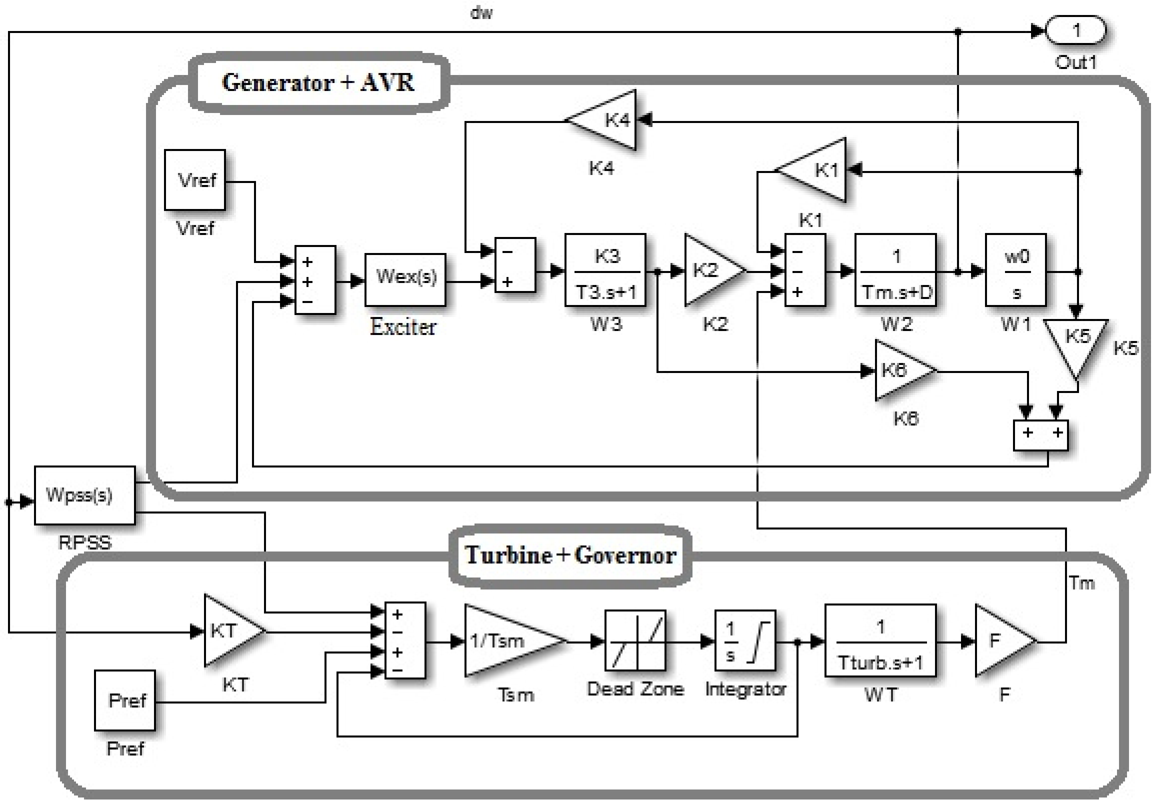

Fig. 1. Circuit for the system stabilizer synthesis

The unit of the robust system stabilizer to be synthesized is designated RPSS. As it is evident from Fig. 1, the system stabilizer acts on both AER and ARSR simultaneously, coordinating generation of an additional electromagnetic moment and the turbine moment which counteracts electromechanic oscillations of the turbogenerator shafting.

Using the circuit, given in Fig. 1, the object model can be represented in the space of states:

$$x = Ax + Bu + Gd$$
$$y = Cx \qquad (1)$$

where $x = (\Delta\theta \quad \Delta\omega \quad \Delta e'_q \quad \Delta e_f)^T$, $u = (\Delta u_{ex} \quad \Delta u_{turb})^T$, $d = (\Delta Vref \quad \Delta Pref)^T$, $y = (\Delta\omega)$. The task is to build a controller $u=K(s)y$, which will be insensitive to changes of the operating point.

Robust analysis and synthesis of the controller requires its representation in a special form of the model with uncertainties [3]. The adequacy of such representation determines, to a great extent, the research results. Depending on the form of representation, all the uncertainties are commonly divided into parametric and frequency uncertainties.

Among all possible uncertainties, in this work we will consider those, which occur due to the model linearization in a single, usually nominal, point of the generator operation in the power system. Such uncertainties are represented in a parametric form, using the above model of the generator and the turbine with the controller [5].

Elements of the model matrices depend on the coefficients, which, in their turn, depend on the operating mode parameters. We represent them in the form of parametric constraints as

$$Ki = \overline{Ki}(1 + m_i \cdot \delta_i), i = \overline{1,4} \qquad (2)$$

where $\overline{Ki}$ – values of the coefficients under nominal conditions of the turbogenerator operation, m_i – certain numbers and δ_i – uncertainties, the module of which is limited to the unit, $|\delta_i| \le 1$. These constraints can be obtained from the formulas of coefficients.

In order to use the algorithm of μ-synthesis of the robust controller, the system is presented in M-Δ configuration according to the known procedure [3] as shown in Fig. 2. The procedure is termed linear fractional transformation and allocates all uncertainties to a separate block. In the scheme of Fig. 2 P is a nominal linearized object, K – the controller to be synthesized, together they form block M(P, K), and Δ-matrix transfer function of the limited system of uncertainties such that $\|\Delta\|_\infty \le \beta$, where $\|\cdot\|_\infty$ is termed H_∞-norm: $\|W(s)\|_\infty = \sup_{\omega\in R}\|W(j\omega)\|_2$, $\|\cdot\|_2$ – spectral norm of the matrix equal to its largest singular number $\bar{\sigma}$. The matrix of the model uncertainties can be structured, i. e. presented in the form of $\Delta = diag[\delta_1 I_{r_1},\ldots,\delta_s I_{r_s},\Delta_1,\ldots,\Delta_f]$, $\delta_i \in C$, $\Delta_j \in C^{m_j\times m_j}$, where the first part is responsible for parameteric uncertainties and the second part – for frequency uncertainties. Our model will include only parametric uncertainties corresponding to the parameters K1 – K6. We designate the set of such structured matrices for the given model as Ω.

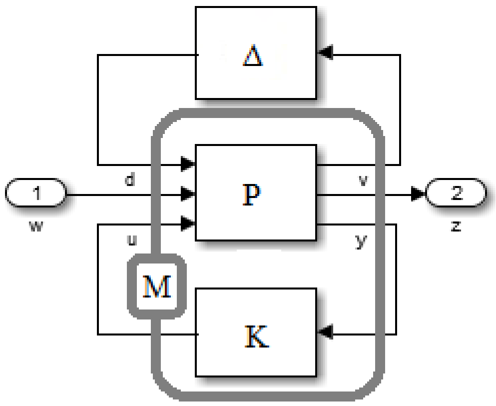

Fig. 2. Standard *M*-Δ configuration with regulator *K*

In the theory of μ-synthesis a notion of structural singular number $\mu_\Delta(M)$ is introduced in the form of $\mu_\Delta(M) = \left[\min_{\Delta\in D}\{\bar{\sigma}(\Delta): det(I - M\Delta) = 0\}\right]^{-1}$, respectively, $\mu_\Delta(M(s)) = \sup_\omega \mu_\Delta(M(j\omega))$. It can be proved that a system with uncertainty $\Delta\in\Omega$ for $\|\Delta\|_\infty \le \beta$ is robustly stable then, and only then, when $\mu_\Delta(M(s)) \le 1/\beta$. Proceeding from this statement, the μ-synthesis algorithm can be formulated.

The aim of μ-synthesis is to find such K(s) of the regulator, which would minimize $\mu_\Delta(M(s))$. There is no direct algorithm of solving this problem, but it may be reformulated into a corresponding H_∞-optimization problem, for which solution procedure exists. This method is referred to as D-K-iterations. For the set of constant matrices D of the same structure as Δ it could be shown that the following inequality holds: $\mu_\Delta(M(s)) \le \inf_D \|DM(P,K)D^{-1}\|_\infty$. However, for each Δ of the fixed matrix D the problem $\inf_{K(s)}\|DM(P,K)D^{-1}\|_\infty$ is a standard H_∞-optimization problem. Therefore, the procedure of D-K-iterations, which solves the *μ*-synthesis problem, has the form of:

1) Setting the initial value of *D*, commonly, a unit matrix ;
2) Fixing *D* and solving the problem of $\inf_{K(s)}\|DM(P,K)D^{-1}\|_\infty$ H_∞-optimization for *K*;

fixing *K* and finding $D(j\omega)$ such that it would approximate the numerical solution of the problems $\inf_{D_i}\|D_i M_i D_i^{-1}\|_2$, found at the chosen frequency grid $\omega_i, i = \overline{1,N}$, where $D_i = D(j\omega_i)$, $M_i = M(j\omega_i)$. Then you pass to step 2 until the sufficient accuracy is achieved.

It should be noted, however, that this algorithm is not always accurate and sometimes gives overestimated value of $\mu_\Delta(M(s))$.

As a rule, the found form of the controller K(s) is of a high order, which is a distinguishing feature of μ-synthesis. To decrease the order of the controller, the Shur complement method could be used.

In MATLAB Simulink software environment with the use of Robust Control Toolbox the authors have developed a software system for implementation of the proposed controller synthesis method, investigation of the controller characteristics and their effects in regular and emergency modes for different power system configurations. The software system comprises a module for synthesis and analysis of the robust controller, using a simplified model of the turbogenerator and power system, and a module for testing transient processes with the application of this controller in the full model of the system, using the library of Simulink SimPowerSystems. The testing module implements the possibility to simulate transient processes with the following options: single- / multiplemachine system, receiving system of infinite / limited power, modes of successful / unsuccessful symmetrical / asymmetrical short circuits with automatic reactivation, load surge, non-synchronous connection of the turbogenerator in the system.

Conclusions

Unlike standard system stabilizers, the controller synthesized using the proposed approach makes it possible to ensure robustness of the system relative to the operating mode parameters, taking into account relationship between AER and ARSR. The applied μ-synthesis algorithm enables ensuring not only robust stability, but also high robust control quality under given uncertainty conditions. The developers implemented the μ-synthesis algorithm in MATLAB software package and, therefore, the above procedures may be realized using the functions of Robust Control Toolbox library. This capability makes it possible to automate transformation of the model under study into the required form as well as the robust controller synthesis process.

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